

HIGGS SEARCHES AT THE TEVATRON

DISCRETE '08 • Valencia, Spain • December 11-16, 2008

Bruno Casal Laraña

Instituto de Física de Cantabria
(CSIC-Univ. de Cantabria)

On behalf of the CDF and DØ
Collaboration



OUTLINE

① Introduction

② Standard Model Higgs

- Low mass
- High mass
- Combination

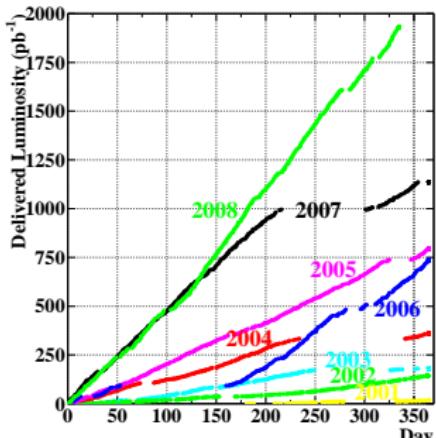
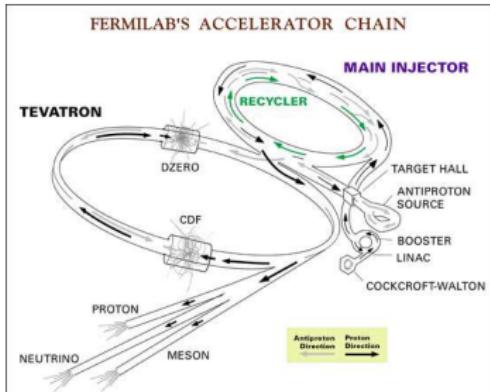
③ Beyond SM Higgs

④ Conclusions



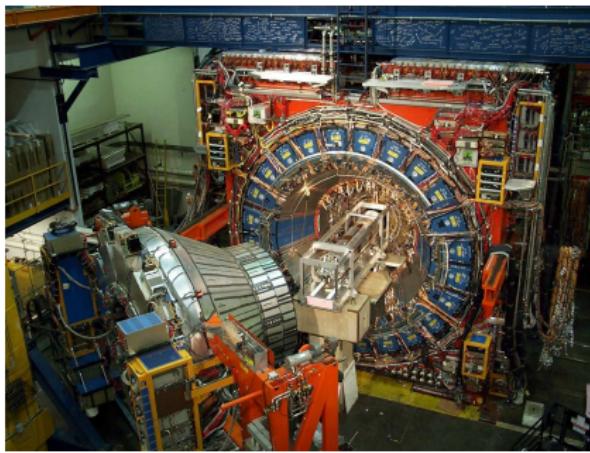
THE TEVATRON AT FERMILAB

- $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
- Peak luminosity $\sim 360 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$
- Tevatron delivered $\sim 5.5 \text{ fb}^{-1}$
- DØ collected $\sim 4.7 \text{ fb}^{-1}$
- CDF collected $\sim 4.5 \text{ fb}^{-1}$
 - Analyses shown here use up to 3 fb^{-1}
- Tevatron is performing extremely well
 - Expected 6-8 fb^{-1} by end of 2009
 - Possibly run in 2010



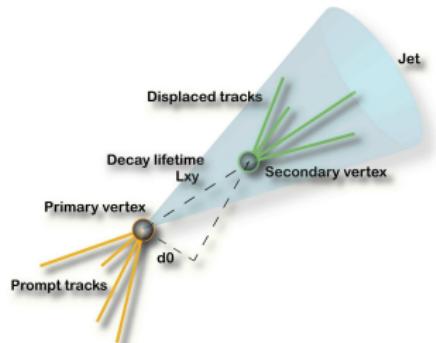
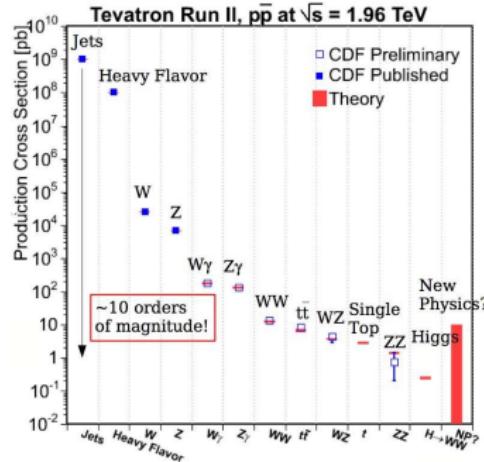
THE CDF AND DØ DETECTORS

- Two multipurpose detectors at Tevatron collecting data efficiently
 - Large acceptance and good ID for leptons
 - Tracking and EM calorimeter
 - Muon systems
 - Good calorimetry for jet energy resolution
 - Silicon detectors for b-jet tagging



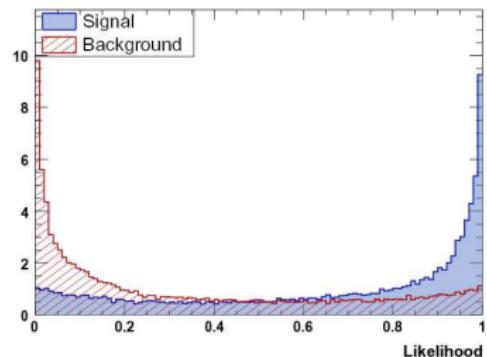
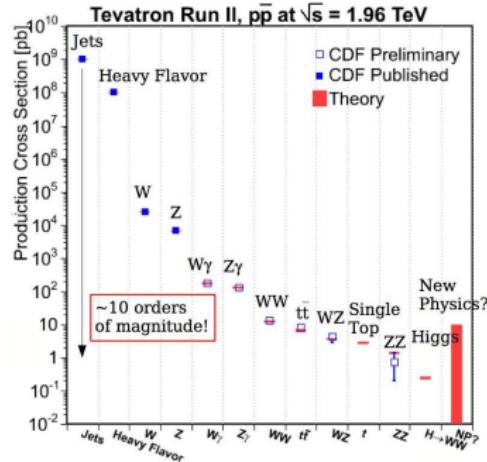
HIGGS SEARCHES AT TEVATRON IN A NUTSHELL

- The Challenge: extract Higgs signal from a background 10 orders of magnitudes larger
- Trigger
 - High p_T leptons (e, μ), MET+Jets, τ dedicated
- Lepton ID: optimized on large W/Z samples
- b -jet tagging
 - DØ: NN tagger based on b -lifetime information, with multiple operating points
 - CDF: Secondary Vertex and Jet Probability algorithms. Additional NN flavor separators
- Background estimation is crucial
 - MC predictions: $W/Z+jets$, diboson, top,...
 - Data driven: mistags, QCD
 - Control regions
- Advance analysis techniques to separate signal from background
 - Neural Network, Matrix Elements, Boosted Decision Trees,...
 - Exhaustive checks in control regions



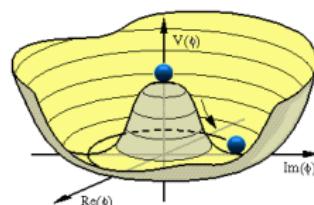
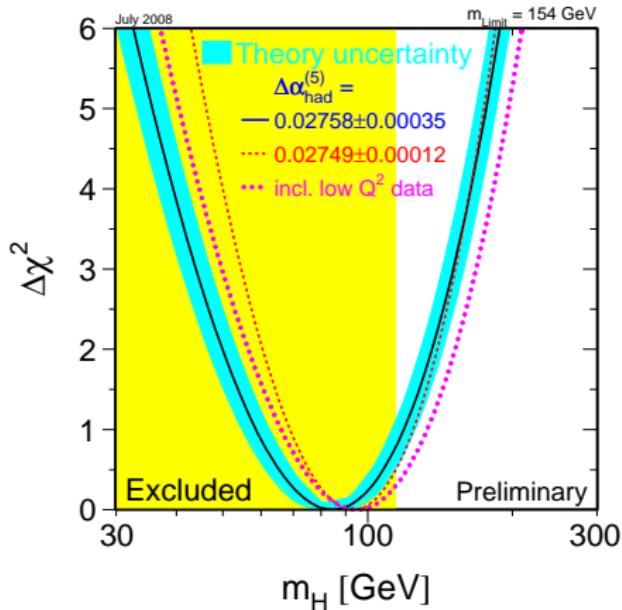
HIGGS SEARCHES AT TEVATRON IN A NUTSHELL

- The Challenge: extract Higgs signal from a background 10 orders of magnitudes larger
- Trigger
 - High p_T leptons (e, μ), MET+Jets, τ dedicated
- Lepton ID: optimized on large W/Z samples
- b -jet tagging
 - DØ: NN tagger based on b -lifetime information, with multiple operating points
 - CDF: Secondary Vertex and Jet Probability algorithms. Additional NN flavor separators
- Background estimation is crucial
 - MC predictions: $W/Z+jets$, diboson, top,...
 - Data driven: mistags, QCD
 - Control regions
- Advance analysis techniques to separate signal from background
 - Neural Network, Matrix Elements, Boosted Decision Trees,...
 - Exhaustive checks in control regions



STANDARD MODEL HIGGS

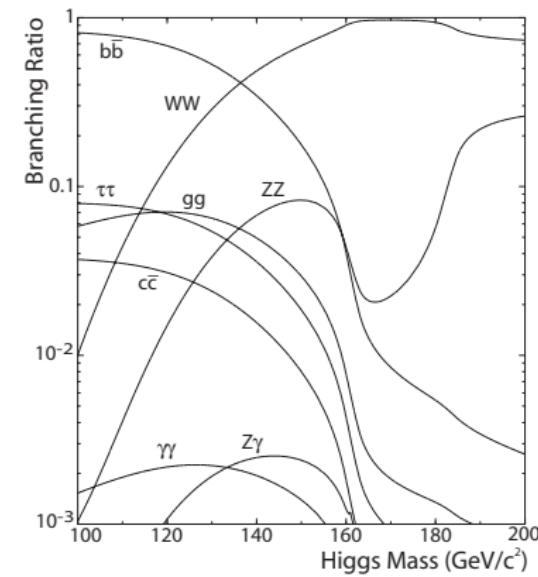
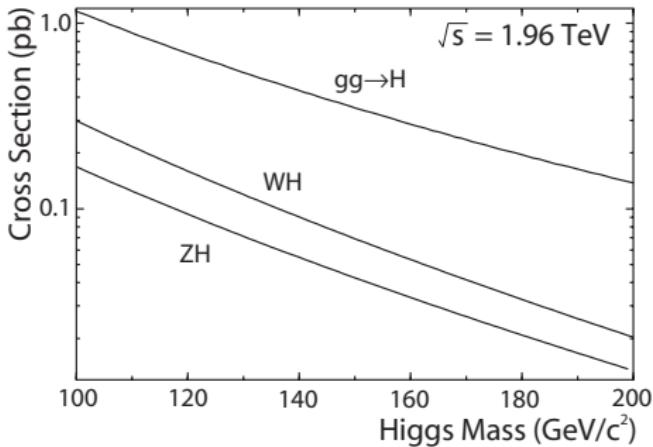
- EW symmetry breaking introduced into the SM via the Higgs mechanism
 - Results in massive **Higgs** boson and mass terms for fermions
 - Not yet observed: opportunity for the Tevatron



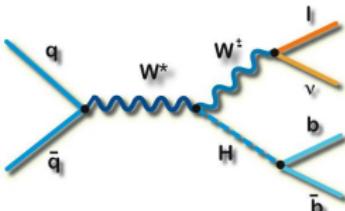
- LEP direct searches:
 $m_H > 114 \text{ GeV}$
- Indirect EW constraints:
 $m_H < 154 \text{ GeV}$

SM HIGGS: TEVATRON PRODUCTION AND DECAY

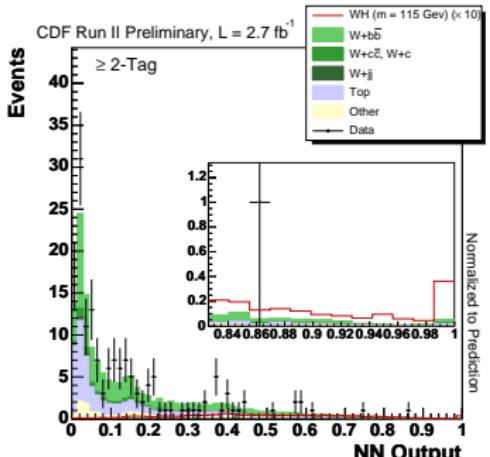
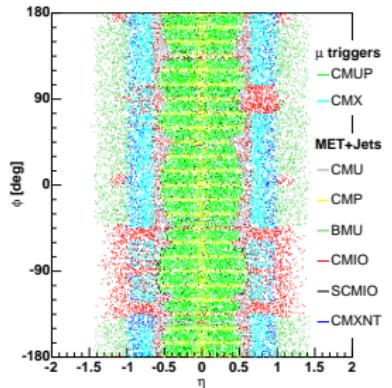
- Low mass ($m_H < \sim 135\text{GeV}$):
 - $H \rightarrow b\bar{b}$ dominant decay
 - $gg \rightarrow H \rightarrow b\bar{b}$ overwhelmed by background
 - Search for associated W/Z production
- High mass ($m_H > \sim 135\text{GeV}$):
 - $H \rightarrow WW$ dominant decay
 - Background low enough to use $gg \rightarrow H$



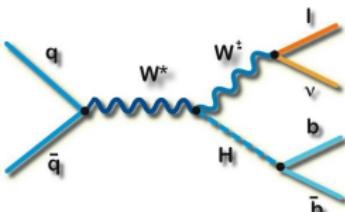
Low MASS: $WH \rightarrow \ell\nu b\bar{b}$



- Signature: 1 high p_T lepton + MET + b-jets
- Most sensitive channel at low mass
- Bkgs: $W+jets$, $t\bar{t}$, single-top, non-W (QCD)
- Extended lepton coverage
- DØ: NN discriminant, allow events with 3 jets
 - NN analysis: split 3 b-tagging categories
 - BDT+ME: exploits kinematic variables + ME info + NN flavor separator
 - Combination of above using evolved NN ($\sim 10\%$ improvement) [new Nov.]
- CDF:



Low MASS: $WH \rightarrow \ell\nu b\bar{b}$

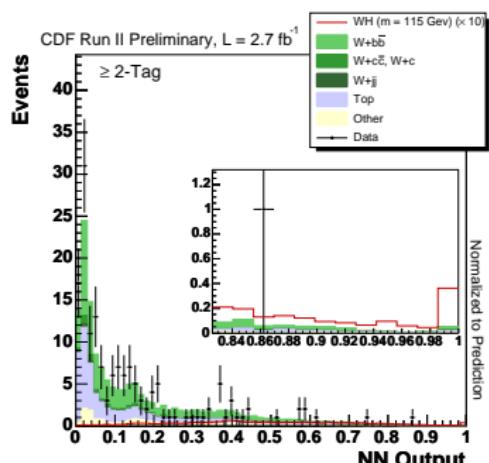


- Signature: 1 high p_T lepton + MET + b-jets
- Most sensitive channel at low mass
- Bkgs: $W+jets$, $t\bar{t}$, single-top, non-W (QCD)
- Extended lepton coverage
- DØ: NN discriminant, allow events with 3 jets
 - NN analysis: split 3 b-tagging categories
 - BDT+ME: exploits kinematic variables + ME info + NN flavor separator
 - Combination of above using evolved NN ($\sim 10\%$ improvement) [new Nov.]
- CDF:

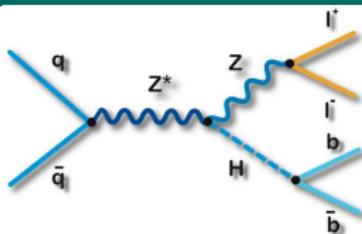
RESULTS

Analysis	Lumi. (fb $^{-1}$)	Exp. Limit	Obs. Limit
DØ NN	1.7	8.5	9.3
CDF NN	2.7	5.8	5.2
CDF ME+BDT	2.7	5.6	5.8
CDF combo	2.7	4.8	5.6

$m_H = 115$ GeV: 95%CL Limit in σ / SM



Low MASS: $ZH \rightarrow \ell^+ \ell^- b\bar{b}$

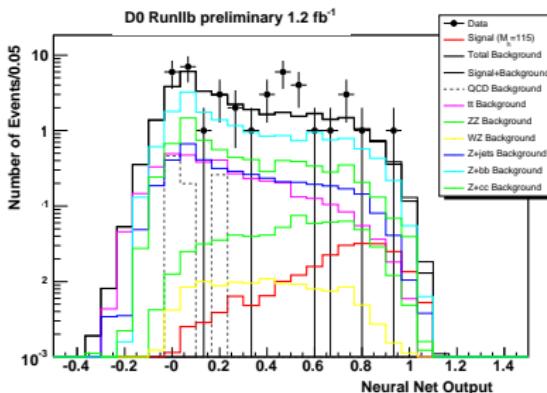


- Signature: 2 high p_T leptons (Z constrain) + b-jets
- Cleanest signature but low event rate
- Main background: $Z+jets$
- Extensive use of loose b-tagging to maximize acceptance
- DØ: NN and BDT discriminants, added 1.2 fb^{-1} of new Run IIb data
 - 2D NN: improved dijet mass resolution with MET projection technique [updated Oct. 2.7 fb^{-1}]
- CDF:
 - New ME analysis

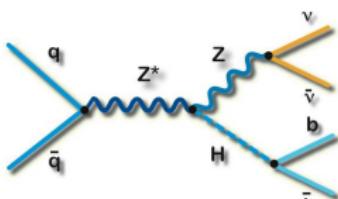
RESULTS

Analysis	Lumi. (fb^{-1})	Exp. Limit	Obs. Limit
DØ NN,BDT	2.3	12.3	11.0
CDF NN	2.7	9.9	7.1
CDF ME (120 GeV)	2.0	15.0	14.2

$m_H = 115 \text{ GeV}$: 95%CL Limit in σ/SM



Low MASS: $VH \rightarrow \text{MET } b\bar{b}$

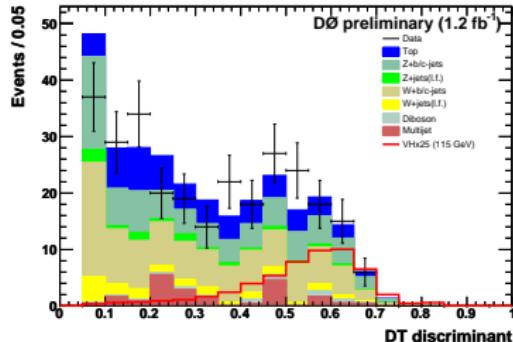
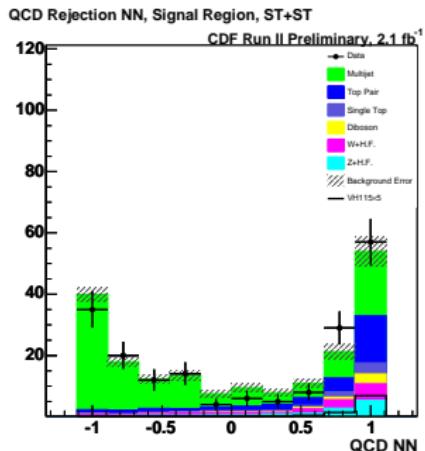


RESULTS

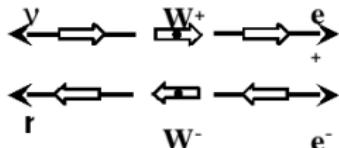
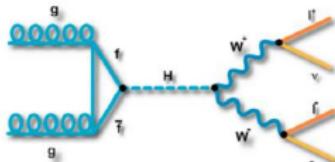
Analysis	Lumi. (fb ⁻¹)	Exp. Limit	Obs. Limit
DØ BD	2.1	8.4	7.5
CDF NN	2.1	5.5	6.6

$m_H = 115 \text{ GeV: 95\%CL Limit in } \sigma / \text{SM}$

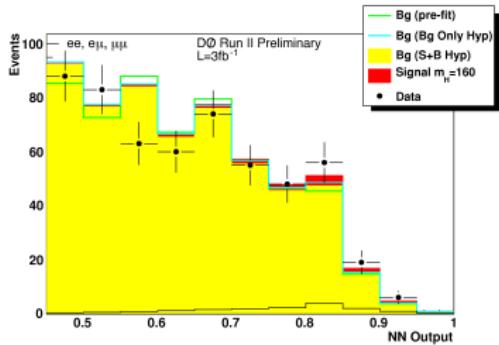
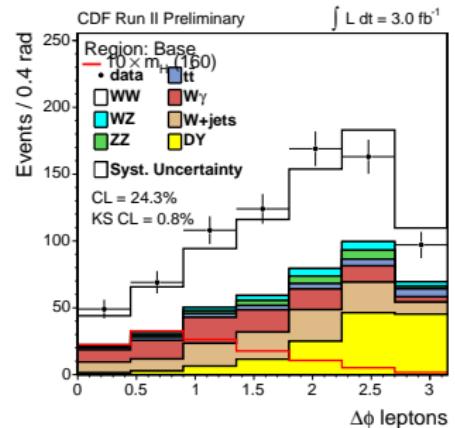
- Signature: large MET + b-jets (lepton veto)
- Sensitive to WH where lepton is undetected
- Challenge: building a model (data driven) for QCD background
- DØ BDT analysis
 - Use NN b-tagger asymmetrically (1 tight, 1 loose tag)
 - Dedicated $W \rightarrow \tau\nu$ analysis
- CDF NN analysis [updated Nov.]
 - QCD-NN with missing-pT to reject background
 - Uses of H1 Jet Algorithm combining tracking and calorimeter information
 - Add 3rd jet to include $W \rightarrow \tau\nu$ acceptance
 - At least one tight tag, split in 3 categories



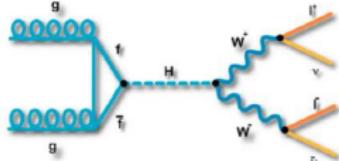
HIGH MASS: $H \rightarrow W^+ W^-$



- Most sensitive Higgs search at the Tevatron
- Signature: 2 high p_T leptons + MET
- Leptons in same directions due to spin correlation
- Also 1 or 2 additional jets: acceptance from associated production and VBF
- Different bkg. composition: WW , Drell-Yan, $t\bar{t}$
- DØ: NN analysis, separate ee , $\mu\mu$, and $e\mu$
- CDF: ME+NN analysis, analyze separately final states with 0, 1 and ≥ 2 jets
- Both experiments approaching SM sensitivity
- Also contributes at lower m_H



HIGH MASS: $H \rightarrow W^+ W^-$

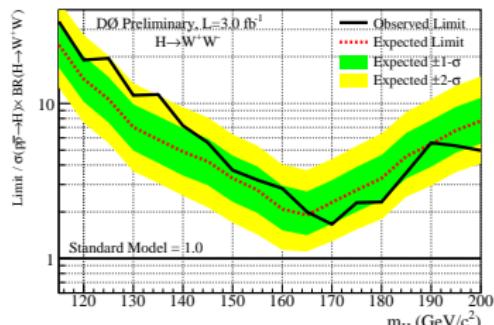
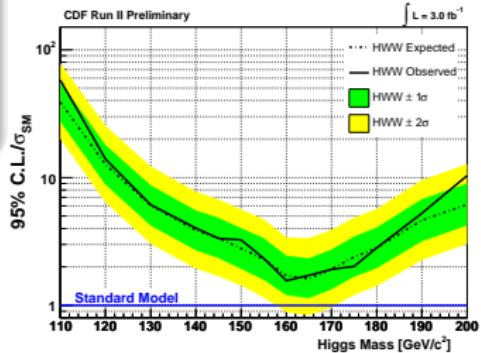


RESULTS

Analysis	Lumi. (fb^{-1})	Exp. Limit	Obs. Limit
DØ NN	3.0	1.9	2.0
CDF ME+NN	3.0	1.6	1.6

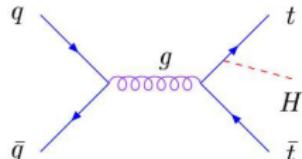
$m_H = 165 \text{ GeV}$: 95%CL Limit in σ/SM

- Most sensitive Higgs search at the Tevatron
- Signature: 2 high p_T leptons + MET
- Leptons in same directions due to spin correlation
- Also 1 or 2 additional jets: acceptance from associated production and VBF
- Different bkg. composition: WW , Drell-Yan, $t\bar{t}$
- DØ: NN analysis, separate ee , $\mu\mu$, and $e\mu$
- CDF: ME+NN analysis, analyze separately final states with 0, 1 and ≥ 2 jets
- **Both experiments approaching SM sensitivity**
- Also contributes at lower m_H



ADDITIONAL CHANNELS

- Many other SM Higgs searches, not as sensitive but contribute in combination

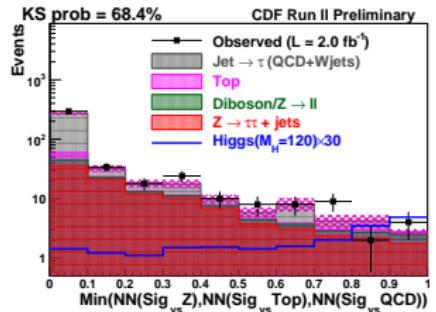
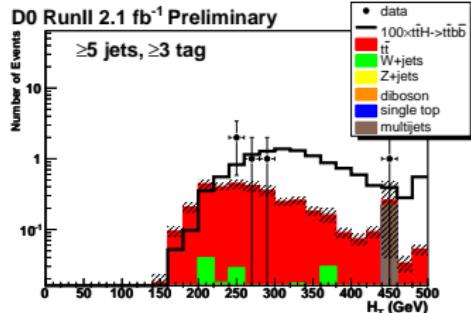


- DØ: $t\bar{t}H \rightarrow \ell bbbbqq$

- Signature: 1 lepton + MET + ≥ 4 jets
- 12 channels
 - $(e, \mu) \times (4, \geq 5 \text{ jets}) \times (1, 2, \geq 3 \text{ b-tags})$
- Scalar sum of jets (H_T) to extract signal
- Obs. (exp.) limit/SM: 63.9 (45.3) at $m_H=115$ GeV

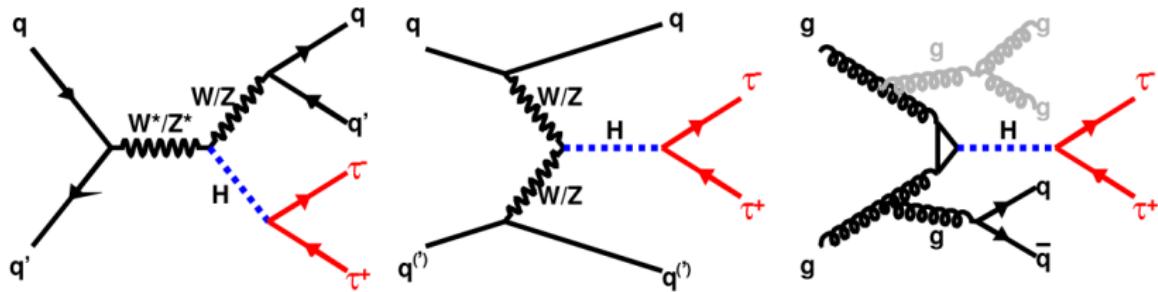
- CDF: $H \rightarrow \tau^+ \tau^- + 2 \text{ jets}$

- Signature: $\tau_{had} + \tau_{lep} + 2 \text{ jets}$
- Simultaneously search VH+VBF+ggH
- Train 3 NN to reject Z , $t\bar{t}$ and QCD
- Obs. (exp.) limit/SM: 30.5 (24.8) at $m_H=115$ GeV

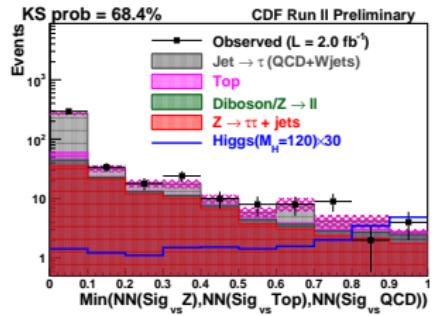


ADDITIONAL CHANNELS

- Many other SM Higgs searches, not as sensitive but contribute in combination

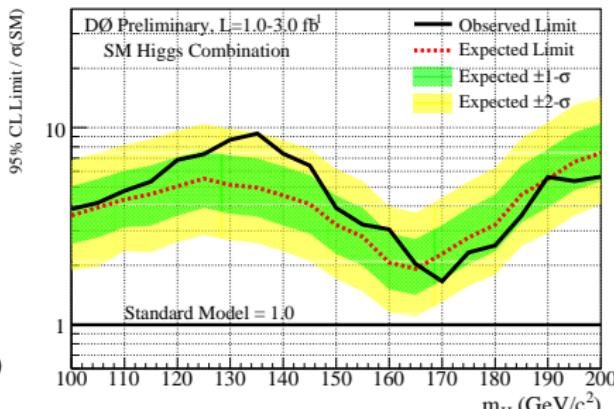
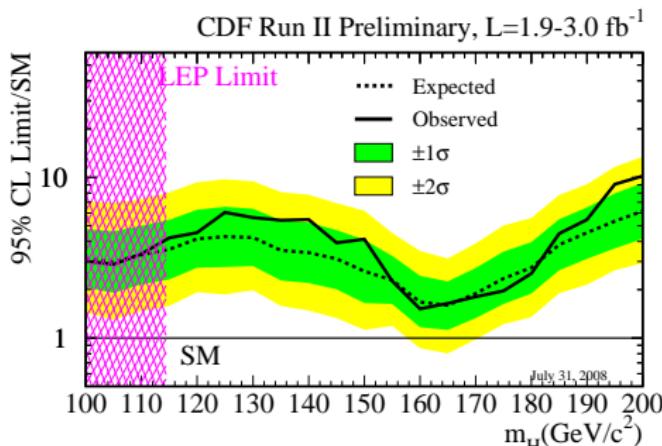


- CDF: $H \rightarrow \tau^+ \tau^- + 2 \text{ jets}$
 - Signature: $\tau_{had} + \tau_{lep} + 2 \text{ jets}$
 - Simultaneously search $VH + VBF + ggH$
 - Train 3 NN to reject Z , $t\bar{t}$ and QCD
 - Obs. (exp.) limit/SM: 30.5 (24.8) at $m_H=115 \text{ GeV}$



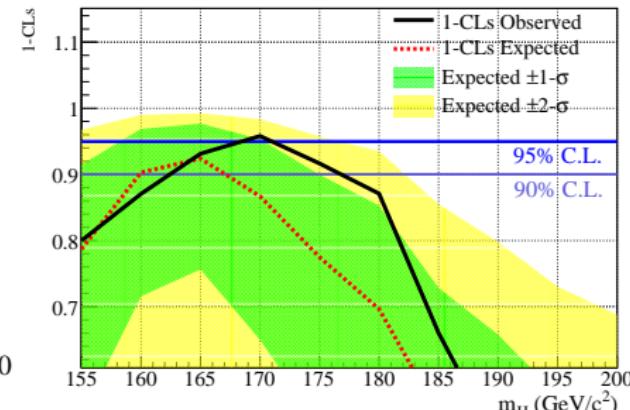
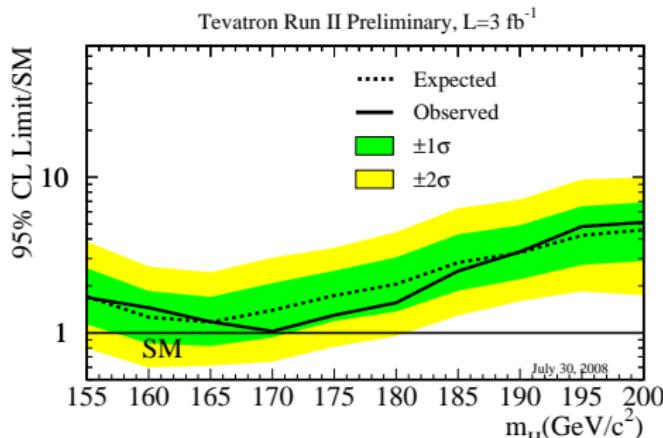
SM HIGGS COMBINED LIMITS

- Bayesian and modified frequentist approaches used
- Systematics and their correlation between channels and experiments taken into account
- Difficult low mass combination, over 70 nuisance parameters
 - CDF combined: expected (observed) limit at 115 GeV: $3.6 \times \text{SM}$ (4.2)
 - DØ combined: expected (observed) limit at 115 GeV: $4.6 \times \text{SM}$ (5.3)
 - Full mass range combination coming soon (expected $< 3.0 \times \text{SM}$ at 115 GeV)
- Tevatron high mass combination
 - We exclude at 95% C.L. the production of a SM Higgs boson of 170 GeV
 - First direct exclusion since LEP!



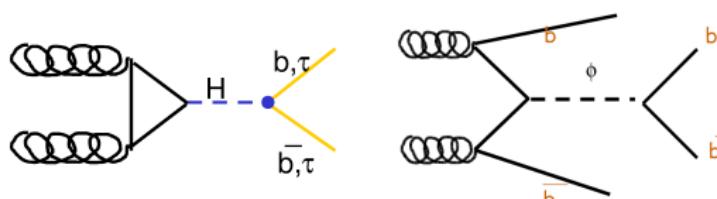
SM HIGGS COMBINED LIMITS

- Bayesian and modified frequentist approaches used
- Systematics and their correlation between channels and experiments taken into account
- Difficult low mass combination, over 70 nuisance parameters
 - CDF combined: expected (observed) limit at 115 GeV: $3.6 \times \text{SM}$ (4.2)
 - DØ combined: expected (observed) limit at 115 GeV: $4.6 \times \text{SM}$ (5.3)
 - Full mass range combination coming soon (expected $< 3.0 \times \text{SM}$ at 115 GeV)
- Tevatron high mass combination
 - We exclude at 95% C.L. the production of a SM Higgs boson of 170 GeV
 - First direct exclusion since LEP!

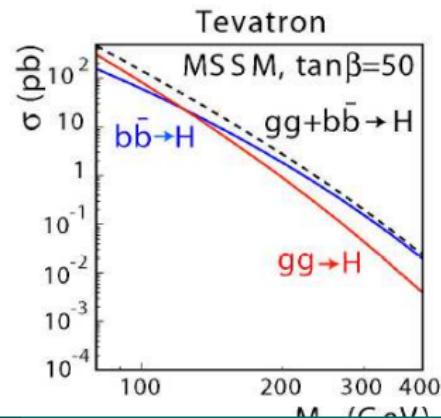
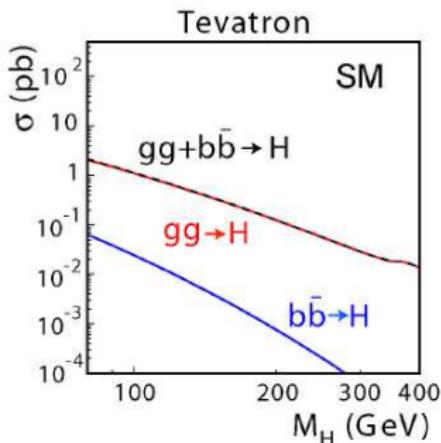


BEYOND THE STANDARD MODEL HIGGS

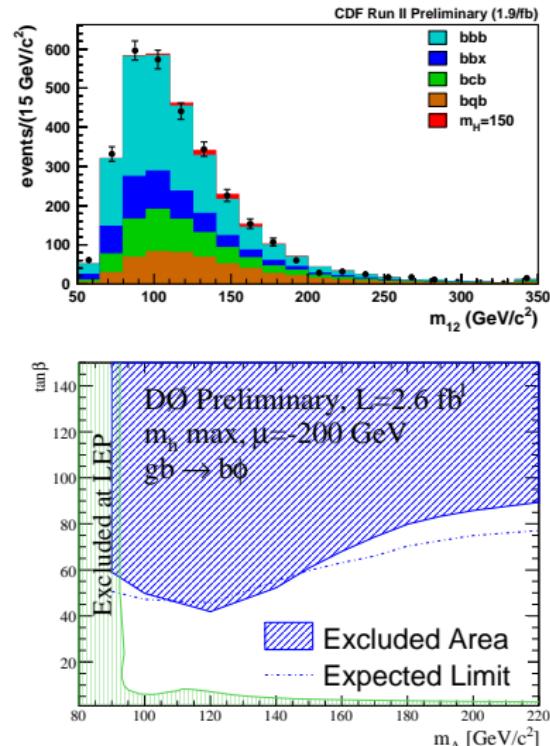
- Many Beyond the Standard Model Higgs possibilities



- MSSM Higgs with enhanced couplings to b quarks and tau leptons at large $\tan \beta$
 - 5 Higgs bosons: h, H, A, H^+, H^-
 - A degenerates with other neutral Higgs at large $\tan \beta$ ($\phi = A, h, H$)
 - Limits $\tan \beta$ vs m_A
- Fermiophobic Higgs with enhanced couplings to W bosons or photons

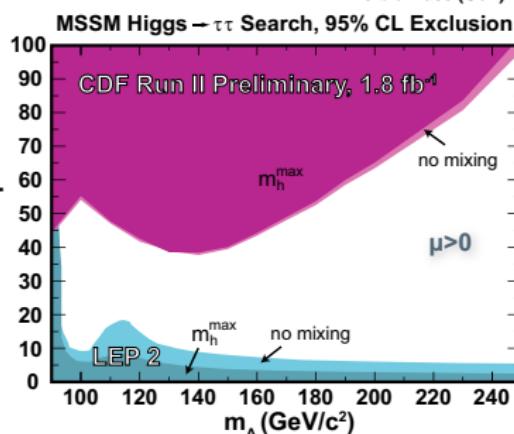
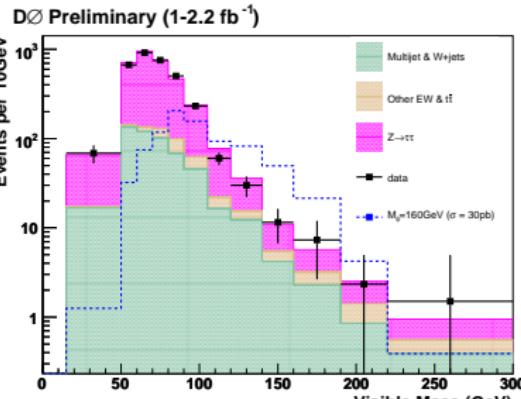


MSSM HIGGS



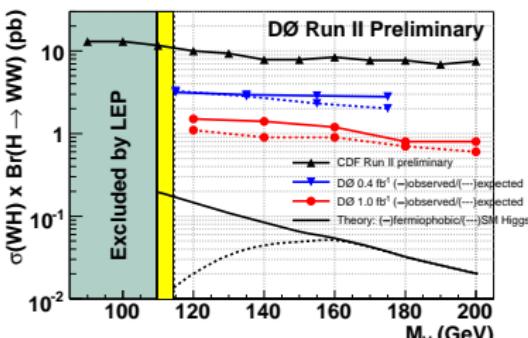
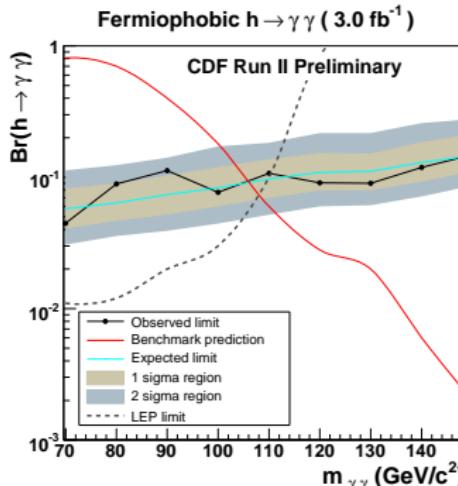
- $b\phi \rightarrow bbb$
 - Require 3 b-jets, Search for peak in di-b-jet mass distribution of leading jets
 - Challenge: understanding quark content of the 3 jets
 - CDF: Vertex mass fits
 - DØ: multiple operating points of NN b-tagger
- $\phi \rightarrow \tau^+ \tau^-$
 - 1 leptonic tau + 1 leptonic or hadronic tau
 - Pure enough to search for direct production
 - Challenge: understanding tau ID efficiency
 - Large W and Z samples for calibrating and testing
- DØ also has a $b\phi \rightarrow b\tau\tau$ search with similar sensitivity

MSSM HIGGS



- $b\phi \rightarrow bbb$
 - Require 3 b-jets, Search for peak in di-b-jet mass distribution of leading jets
 - Challenge: understanding quark content of the 3 jets
 - CDF: Vertex mass fits
 - DØ: multiple operating points of NN b-tagger
- $\phi \rightarrow \tau^+ \tau^-$
 - 1 leptonic tau + 1 leptonic or hadronic tau
 - Pure enough to search for direct production
 - Challenge: understanding tau ID efficiency
 - Large W and Z samples for calibrating and testing
- DØ also has a $b\phi \rightarrow b\tau\tau$ search with similar sensitivity

FERMIOPHOBIC HIGGS



- $H \rightarrow \gamma\gamma$
 - Photon energy resolution better than jets
 - Look for peak in di-photon mass
 - SM-like search but branching ratio is enhanced in fermiophobic model
 - DØ: 2.7 fb^{-1}
 - CDF: 3.0 fb^{-1} [new]
- $WH \rightarrow WW^+ W^-$
 - Look for same-sign leptons
 - Also sensitive to SM at high mass
 - At low mass more sensitive if H is fermiophobic
 - DØ: 1.1 fb^{-1}
 - CDF: 2.7 fb^{-1} [new just blessed]
- Important contribution to SM combo

CONCLUSIONS

- Exciting era for Higgs Searches at the Tevatron
- Both experiments are thoroughly searching for every SM and BSM Higgs boson
- Reaching sensitivity to SM Higgs over full mass range
- No evidence for signal found yet
- Limits ~ 3 times above SM at low mass
- We exclude at 95% C.L. the production of a SM Higgs boson of 170 GeV
 - Wider exclusion zone will follow soon (if no evidence)
- Tevatron performing well, luminosity increasing fast
- Steady improvements since 2005, and still in progress
- Stay tuned!
- Details available at:
 - <http://www-cdf.fnal.gov/physics/new/hdg/hdg.html>
 - <http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm>

